Physics at a Higgs Factory & Linear Colliders

Tao Han
University of Pittsburgh

Snowmass Agora on Future Colliders:
Linear e^+e^- Colliders
December 15, 2021

With the discovery of the Higgs boson:

First time ever, we have a consistent theory:

- **relativistic & quantum mechanical**
- **renormalizable, unitary, vacuum (quasi) stable**

**potentially valid up to an exponentially high scale,
possibly to the Planck scale M_{Pl} !**

**Yet, there are fundamental questions/puzzles
to be answered, conceivably with physics
not far above the Electro-Weak scale.**

• Higgs boson mass & the EW scale

The Higgs field gives ALL elementary particles masses, then who gives the Higgs a mass?

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

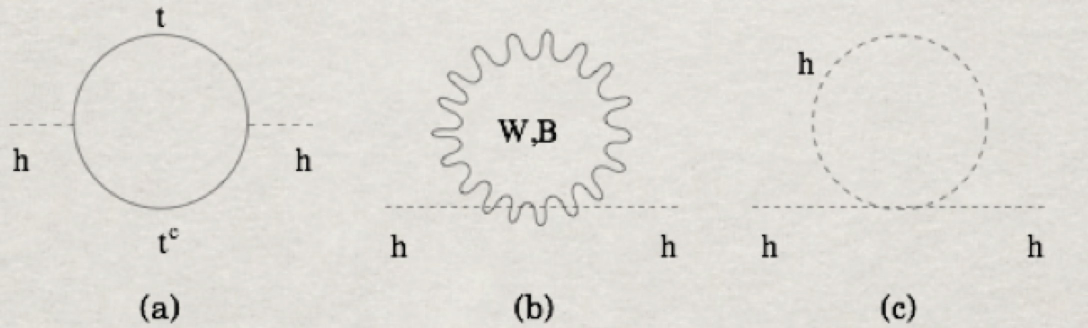
$$\langle\Phi\rangle \Rightarrow \; v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2 \approx (125 \text{ GeV})^2 \;\; \Rightarrow \mu \approx 89 \text{ GV}, \;\; \lambda \approx \frac{1}{8}.$$

The SM as an Effective Field Theory valid to a scale ***Λ***, the Higgs mass is "naturally" dictated by this scale:

$$c_2\Lambda^2 \sim m_h^2 : \;\; \lambda v^2 \sim \mu^2 \sim (100 \text{ GeV})^2 \sim (10^{-16} M_{\text{Planck}})^2$$

In calculating $\mathrm{m}^2{}_{\mathrm{H}}$:



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2}\lambda^2\Lambda^2 \quad + \frac{\kappa^2}{16\pi^2}\Lambda_{BSM}^2 + \ldots$$

The "Naturalness" consideration implies ***Λ*** not too far from v.
Otherwise → "hierarchy problem" between two scales:
Large hierarchy: $v \ll M_{Planck}$; Little hierarchy: $m_H \ll \Lambda_{BSM}$(TeV?)

• Higgs coupling & the EW phase transition

In the SM, $m_H = \sqrt{2\lambda}v = 125$ GeV → $\lambda_{hhh} \sim 0.13$

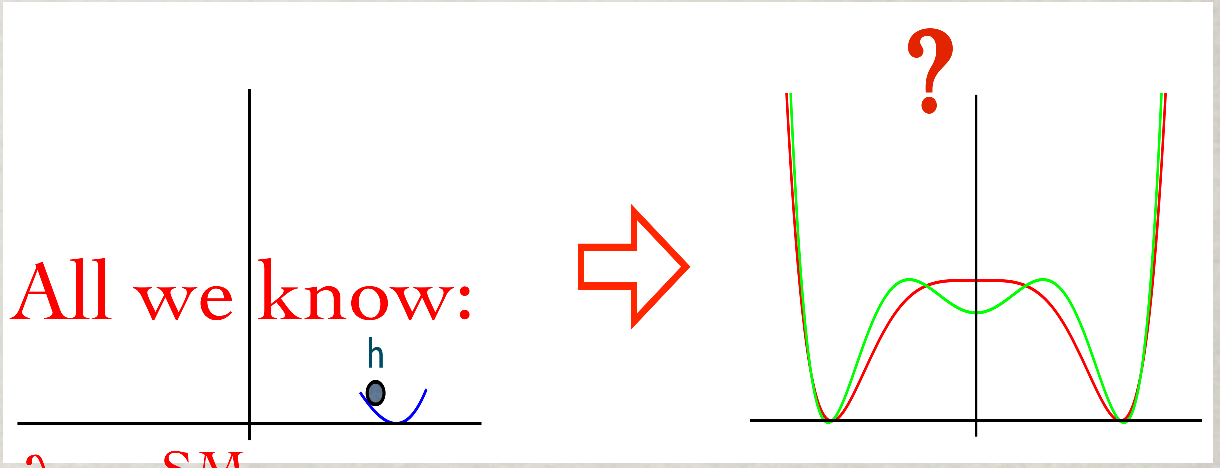
This is a **genuine self-interaction, a "fifth force"!**

But who sets its value?

- In SUSY @ leading order, the symmetry sets
  $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.075$ ← inconsistent with observation.
- In composite model, the Higgs is a pseudo-Goldstone boson,
  → λ dynamically generated.
- With new physics at **Λ**:

$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3,$$

$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right] \quad \to \lambda_{hhh} \sim 2\,\lambda_{hhh}^{SM}$$



Important consequences:

- O(1) modification from λ_{hhh}^{SM} could render the electroweak phase transition strong 1st order!
- Possible electroweak baryogenesis?
- Gravitational wave signals? Inflation?

• Yukawa couplings: The large & small

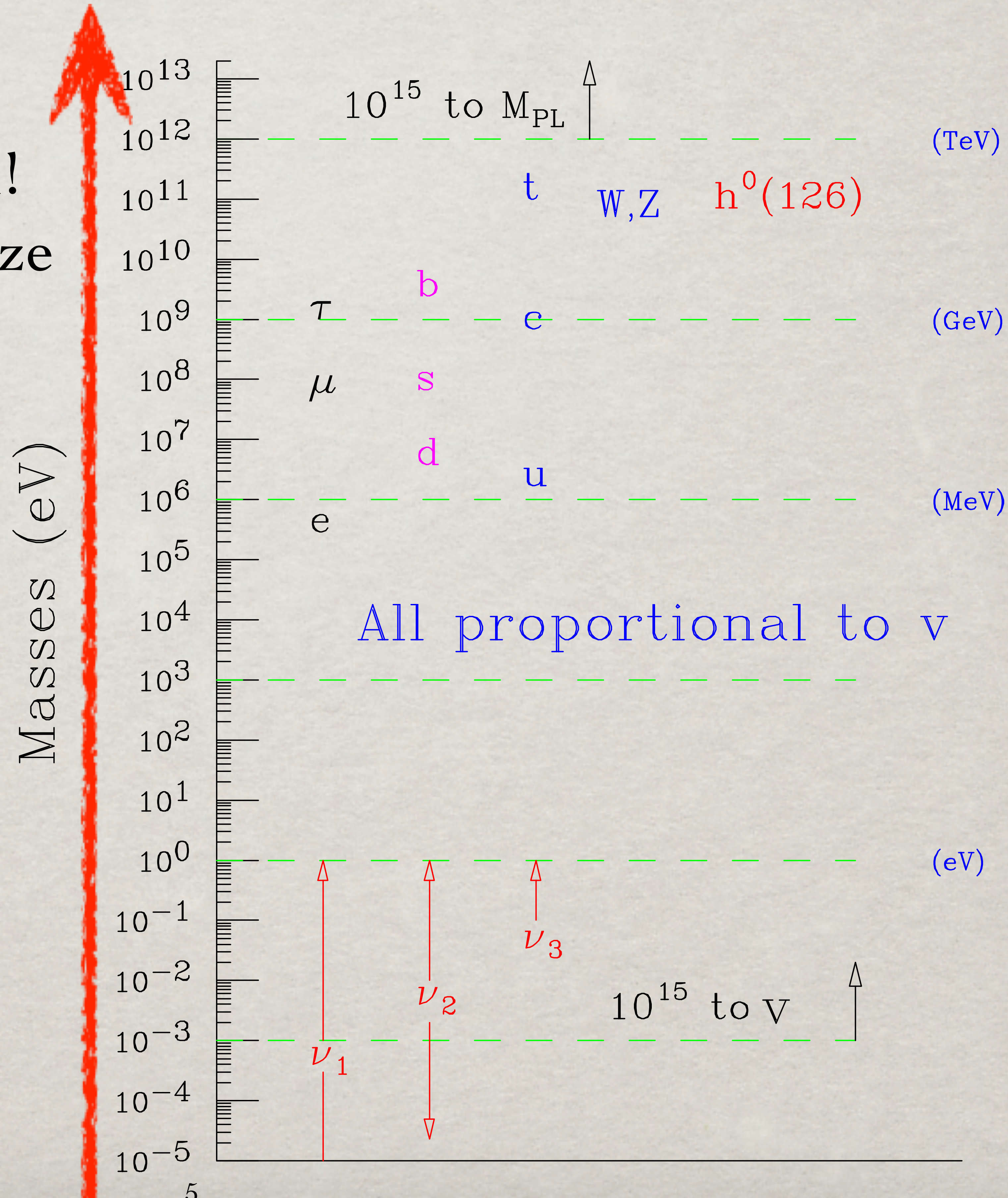
➢ The top quark: $y_t \approx 1$
the largest coupling in SM!
Any siblings to help stabilize
Higgs mass / potential ?

$$(\tilde{t}, \tilde{b}),\ (T', B')...$$

➢ Neutrinos: $y_\nu < 10^{-12}$?
or a new mechanism,
like the "seesaw"
with a physics scale:

$$m_\nu \approx \frac{y_\nu^2 v^2}{M}$$

Higgs is in a pivotal position.



• Higgs portal to unknowns?

The Dark Matter ?

$H^\dagger H$ is the only bi-linear SM gauge singlet (uncharged).

Bad: May lead to hierarchy problem w.r.t. high-scale physics;

Good: May readily serve as a portal to the dark sector:

(a dark scalar S or a fermion χ)

$$k_s H^\dagger H \; S^* S, \quad \frac{k_\chi}{\Lambda} H^\dagger H \; \bar{\chi}\chi.$$

Important consequences:

- Dark matter direct detection:
  spin-independent signals via the Higgs exchange
- Can be consistent with the dark matter relic abundance
- Higgs boson decay to invisible dark matter
- Modification to the Higgs coupling, thus electroweak phase transition, electroweak baryogenesis? Gravitational wave signals?

• Target accuracies:

Tree-level heavy new physics:

$$\Delta\kappa = \frac{g_{BSM}}{g_{SM}} - 1 \sim \mathcal{O}(\frac{v^2}{\Lambda^2}) \approx \frac{6\%}{(\Lambda/\mathrm{TeV})^2}$$

Quantum-level new physics:

$$\kappa_{loop} \sim \frac{1}{(4\pi)^2} \approx 0.6\%$$

Most wanted coupling, hopefully to reach:

$$\lambda_{hhh} < 10\%$$

All complementary to direct searches!

• A Higgs factory is a must !

ANY elementary particle needs a factory to scrutinize:

- Pion/Kaon (μ,ν) factories: CERN, TRIUMF, FNAL, JLab …
- tau/charm factories: CESR, BEPC …
- B-factories: Belle, BaBar, LHCb …
- $Z/W^{\pm}$ factories: SLC, LEP-I, LEP-II, Tevatron, LHC …
- Top-quark factories: Tevatron, LHC.

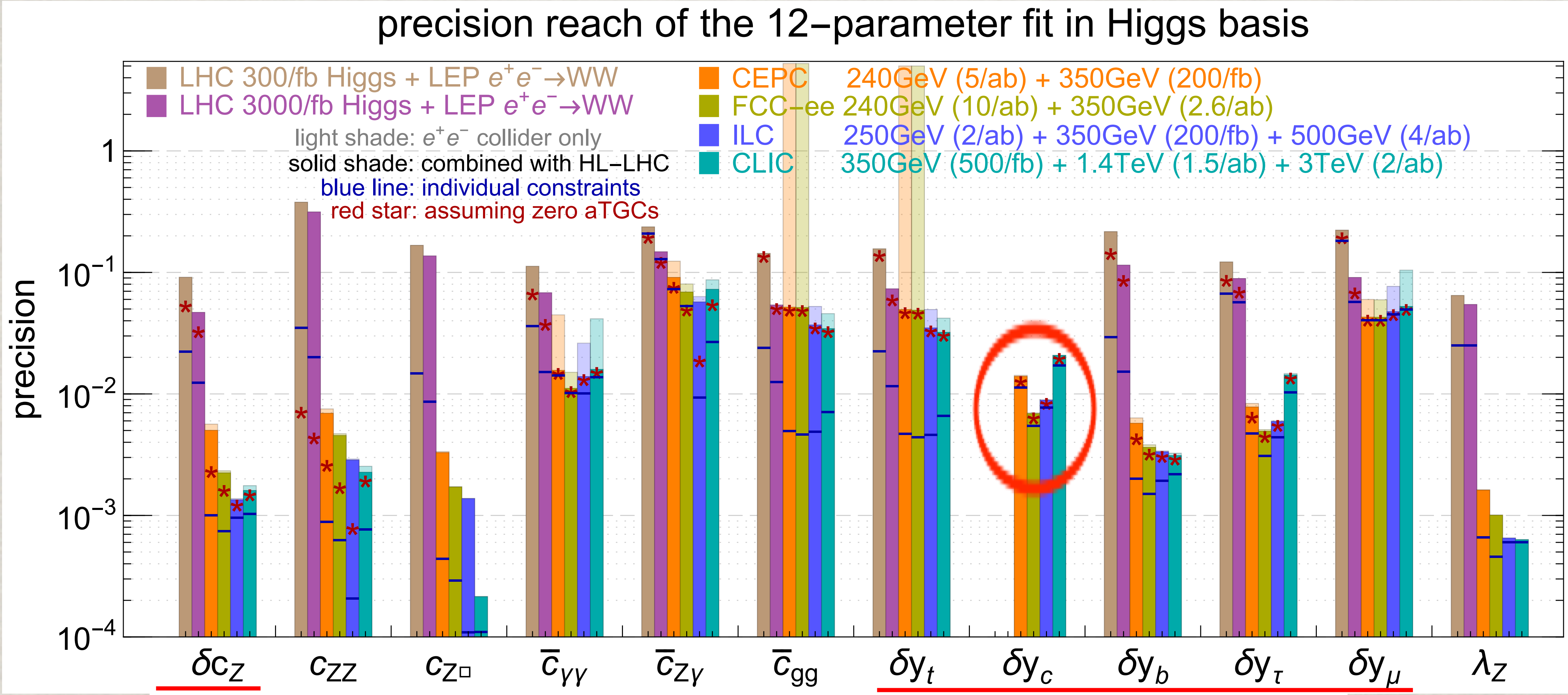
The Higgs boson is NO exception !

LHC Run 3 / HL-LHC will lead the way: 50M/ab !

We need O(10^5 - 10^6) "clean" Higgs bosons:

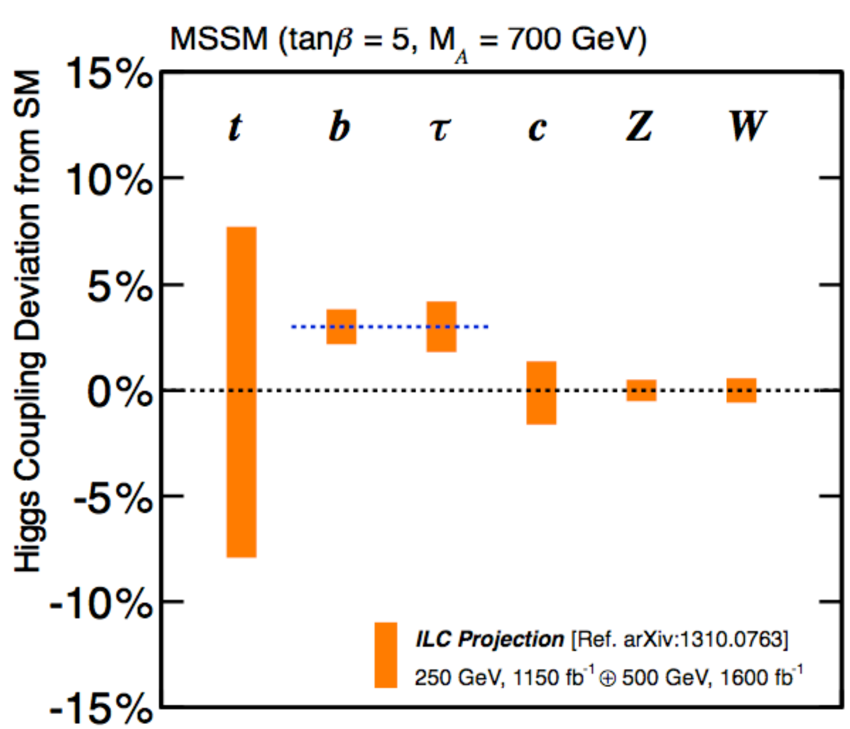
- well-constrained kinematics in e^+e^- collisions
- model-independent, absolute measurements
- sub-percentage accuracy
- challenging decay processes $H \to \tau^{\pm}\mu^{\mp}, c\bar{c}, \ldots$

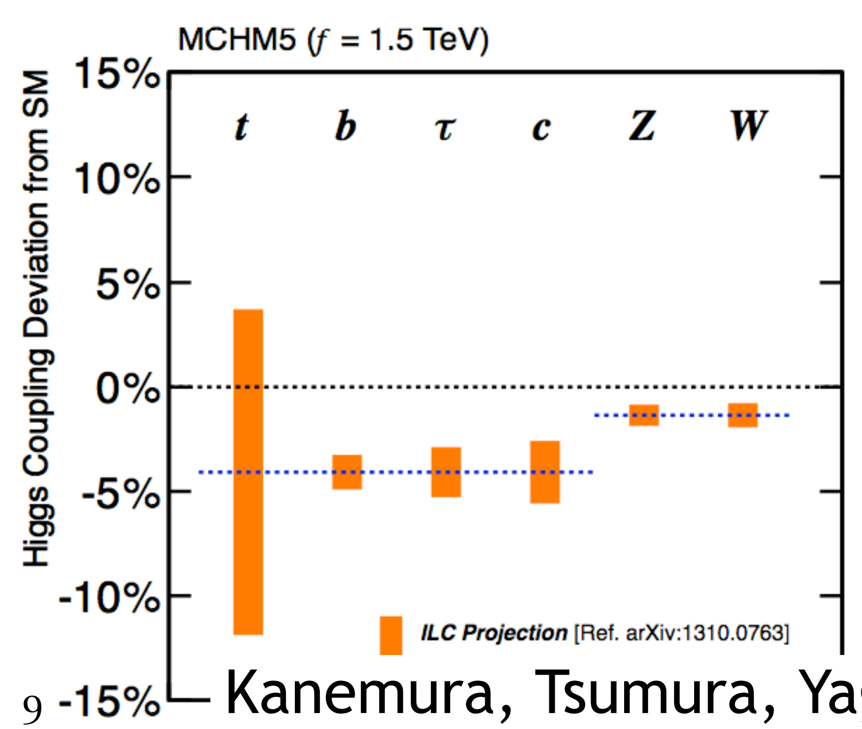
Couplings to sub-percent accuracy: Grojean et al. 1704.02333



SUSY

Composite Higgs





Kanemura, Tsumura, Yagyu, Yokoya

• Higher energy at a linear collider matters

- ILC: 500 GeV, 4 ab^{-1}, 80% / 30% polarization.
- CLIC: 380 GeV, 0.5 ab^{-1}, 80% / 0 polarization.
  1.5 TeV, 1.5 ab^{-1}; 3 TeV, 3 ab^{-1}.

➢ $t\bar{t}$ threshold:
combining threshold scan and top-reconstruction:

$\Delta m_t < 50$ MeV, $\Delta \alpha_s < 1\%$

→ Sufficient to decide on the SM vacuum stability!

➢ Triple Higgs coupling sensitivity:

	ILC arXiv:1506.07870		CLIC Report: 1307.5288v3	
	0.5 TeV	1 TeV(2 ab^{-1})	1.4 TeV	3 TeV
λ_{hhh}	26%	10%	21%	10%

→ Precision test of the shape of the Higgs potential, help to reveal the nature of EW phase transition.

• Other potential discoveries at the e^+e^- precision / energy frontier:

- SM Higgs: CP property determination by kinematics
- Energy threshold for new heavy particles:
  Higgs H^0A^0, H^+H^-; SUSY particles; quarks / leptons reaching $M \sim E_{cm}/2$.
- Beam polarization important:
  determining the chiral (left-right) couplings.
- Contact interaction / composite scale ~ 50 TeV

EPJ-C: arXiv:1504.01726;
arXiv:1709.06103; arXiv:1907.04311
ILC: arXiv:1908.11299
CLIC: arXiv:1812.02093

Summary

- **HEP is in an exciting time:**

  The SM is complete, and is potentially valid to a very high energy scale. Yet, there are strong indications for the existence of new physics not far above the EW scale.

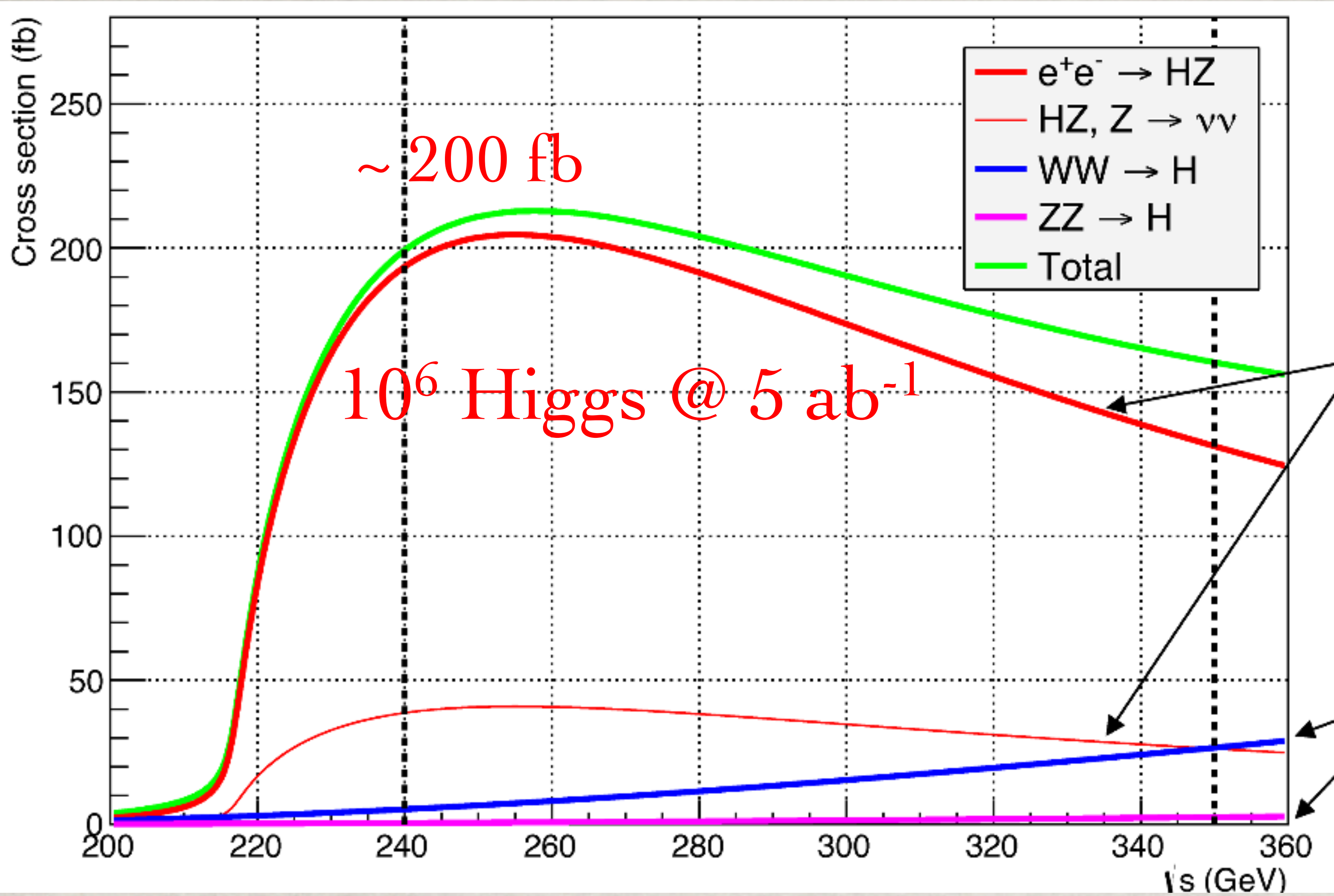
- **The Higgs factory ~250 GeV is the clear target:**

  → New physics under the Higgs lamp-post.

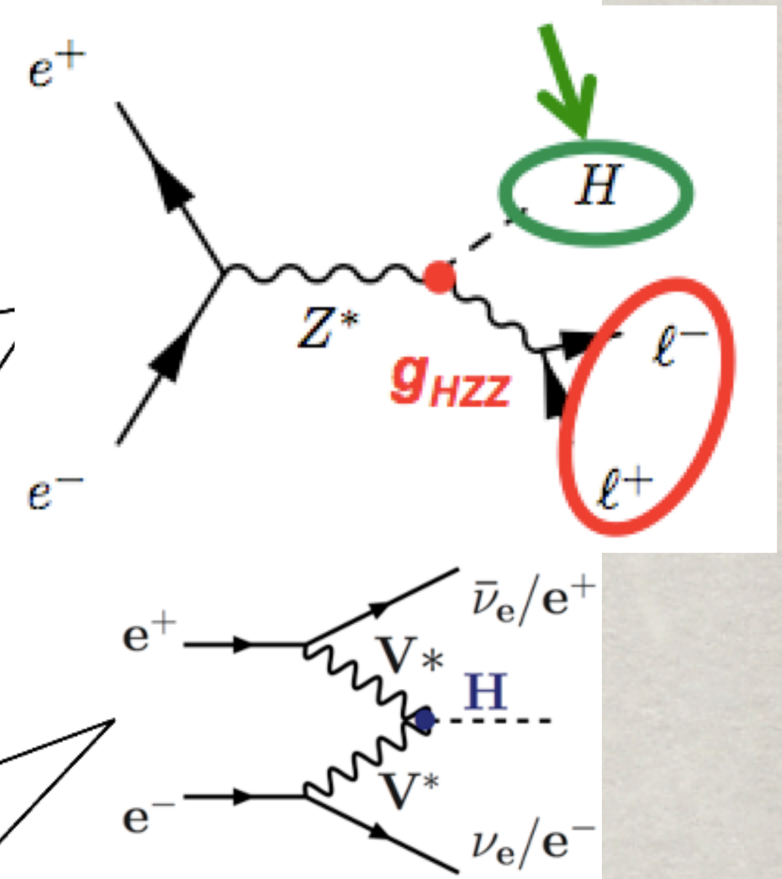
- **Higher energy linear colliders offer great opportunities for discoveries for BSM physics.**

Exciting journey ahead !

Backup Slides

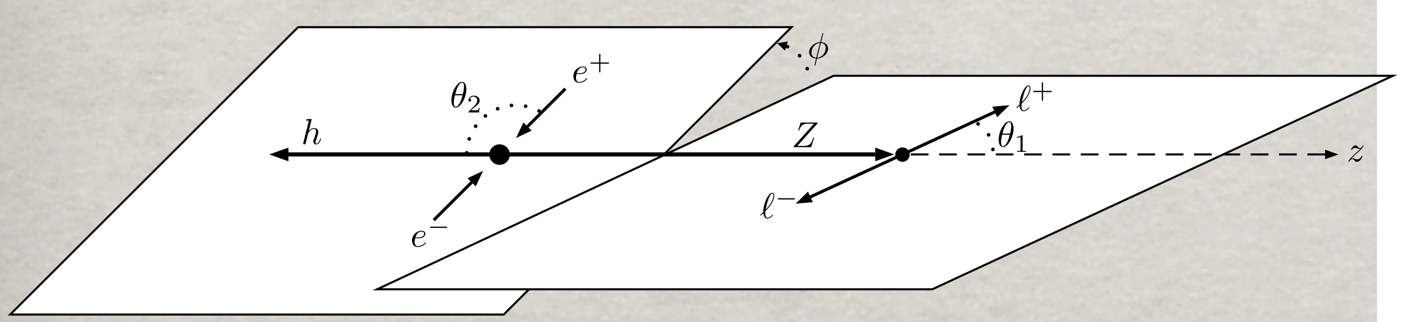


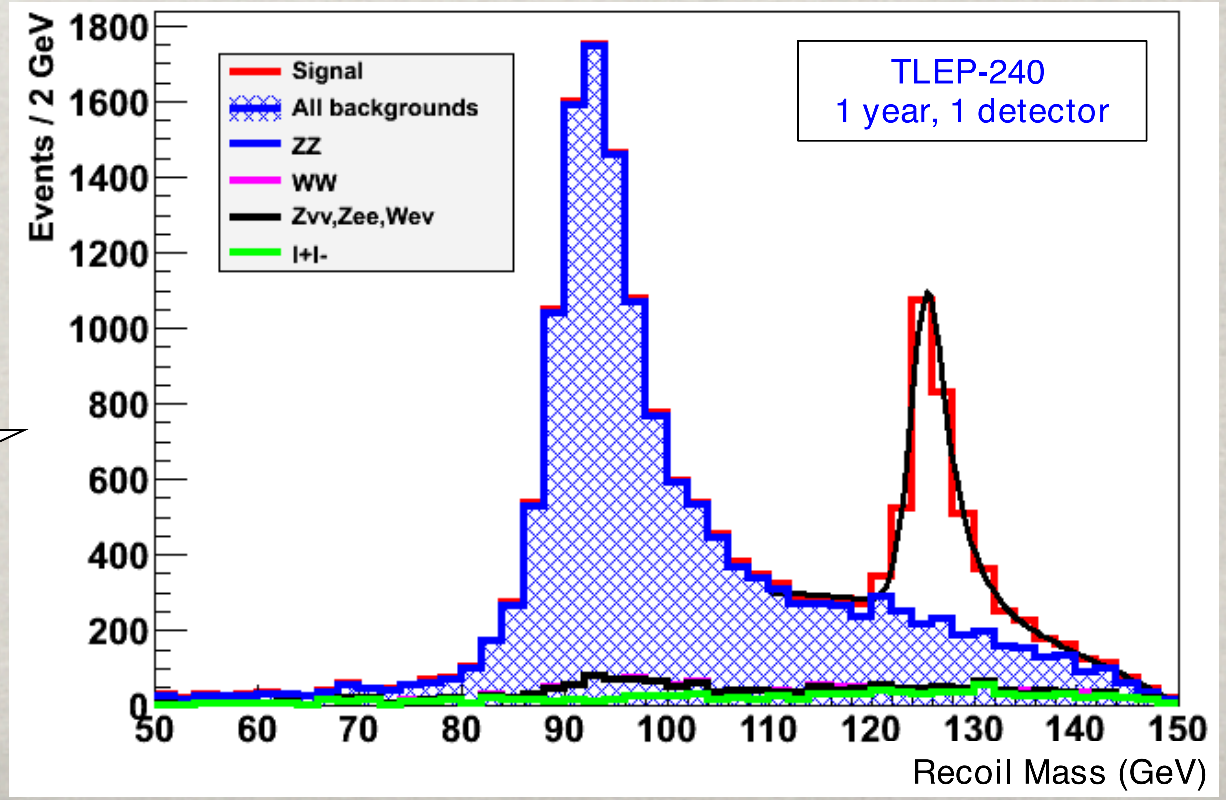
TLEP Report: 1308.6176



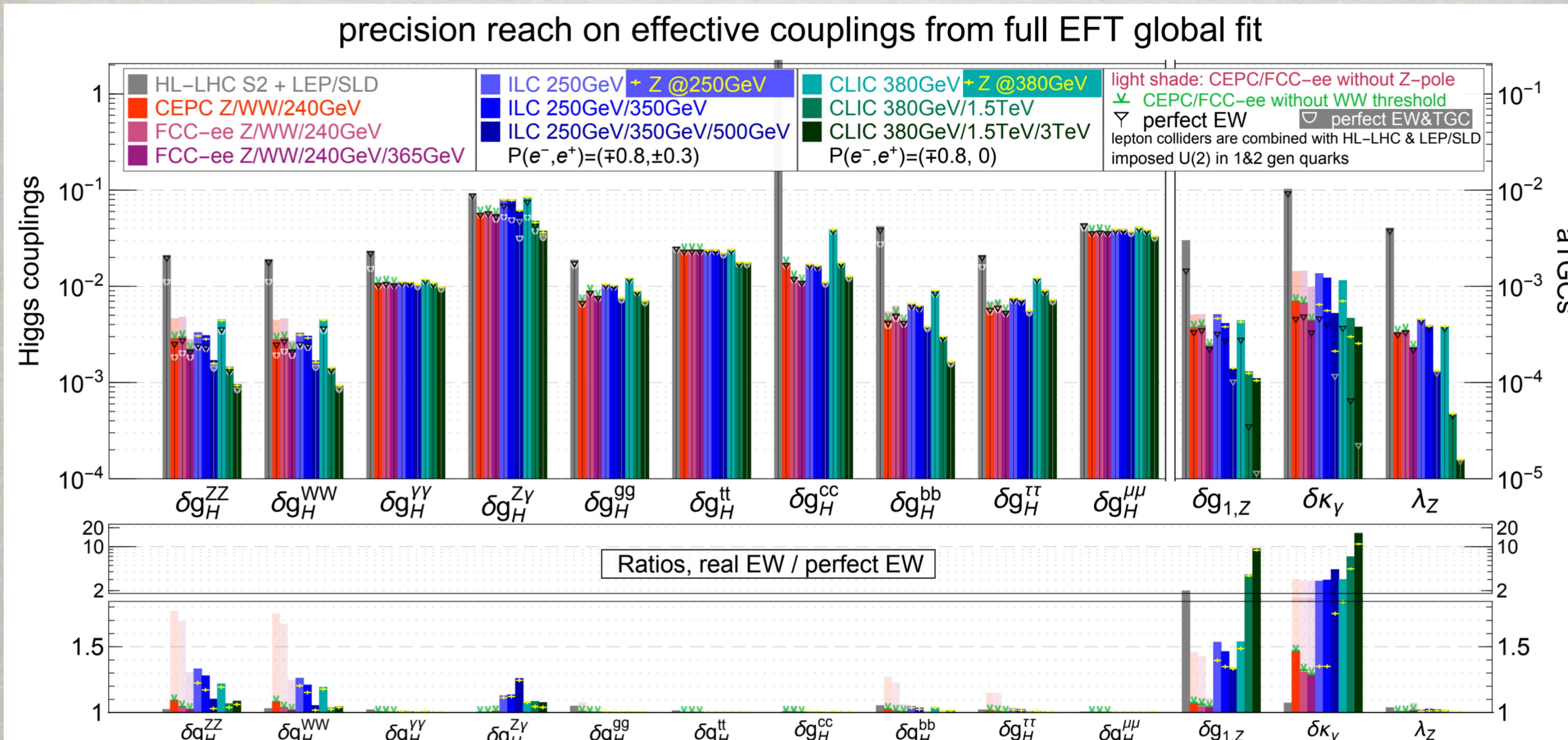
"Recoil mass"

$$m_h^2 = (p_{e^-} + p_{e^+} - q_{\mu^-} - q_{\mu^+})^2$$





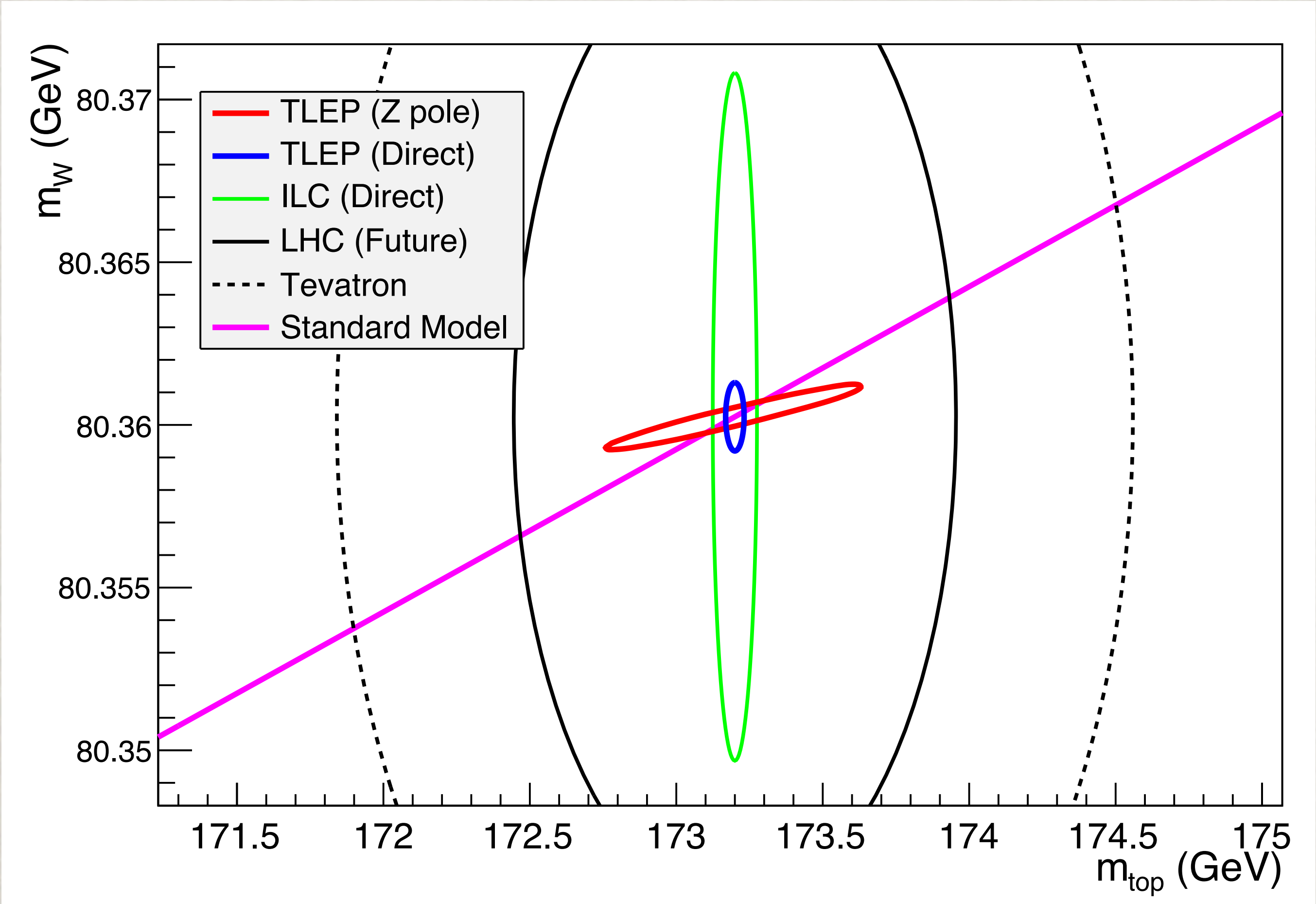
• sensitivity comparison



https://arxiv.org/pdf/1907.04311.pdf

- **W^+W^- threshold scan (10^8 W's)**

$\Delta M_W \sim O(1\ \text{MeV})$, $\Delta m_t \sim O(10\ \text{MeV})$, $\Delta m_H \sim O(10\ \text{MeV})$.

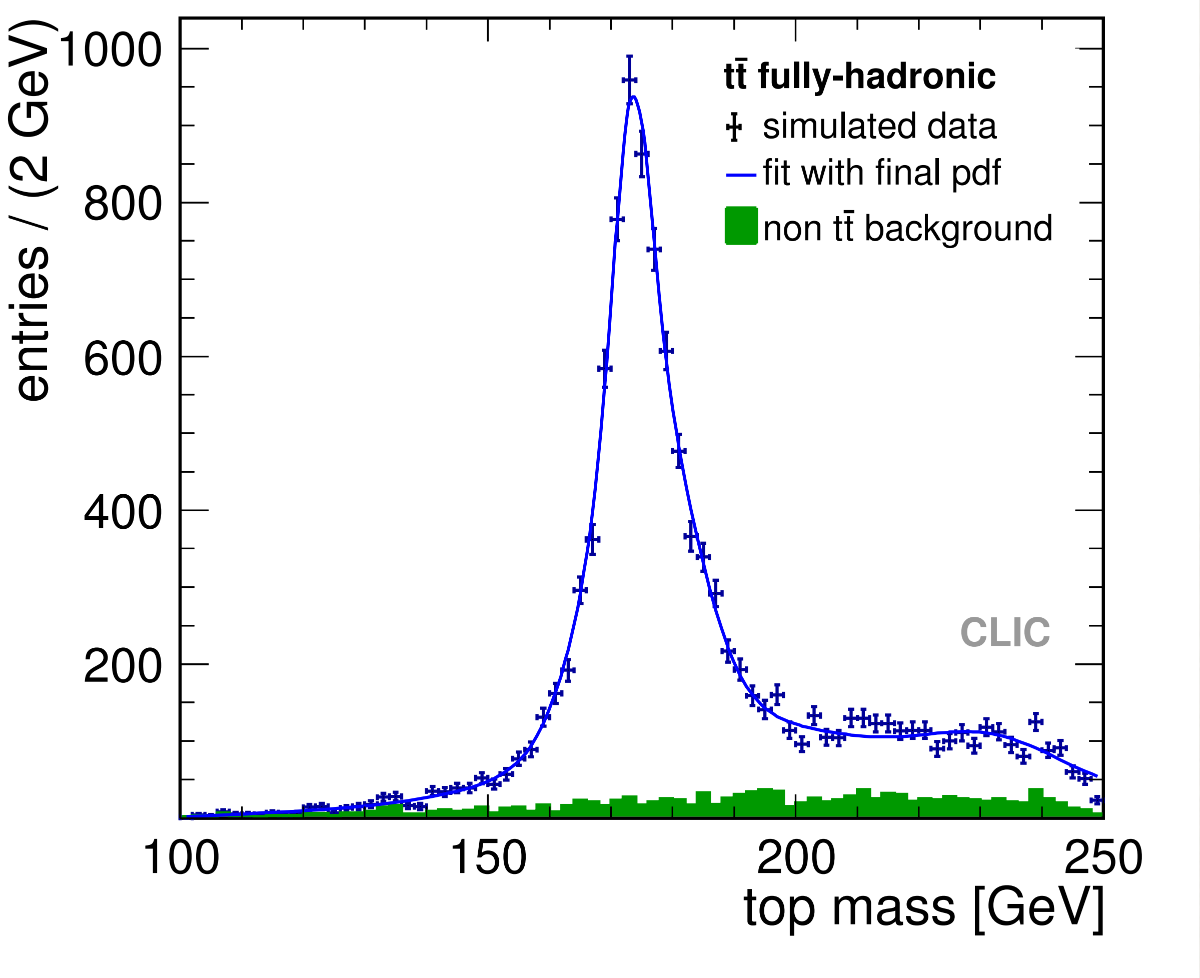


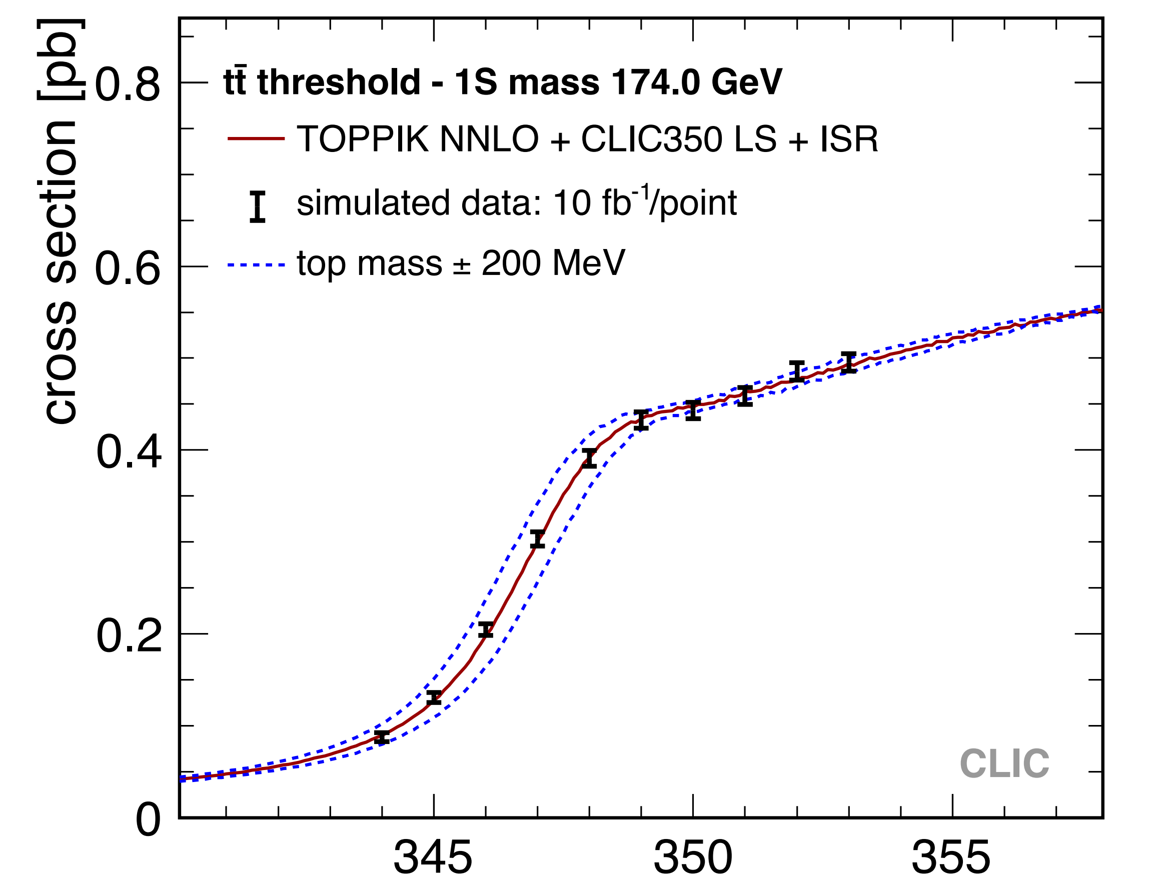
(definitive test for the SM vacuum stability)

TLEP Report: 1308.6176; EW WG Report: 1310.6708

• Top-quark Threshold

ILC: 1604.08122; CLIC: 1307.5288v3

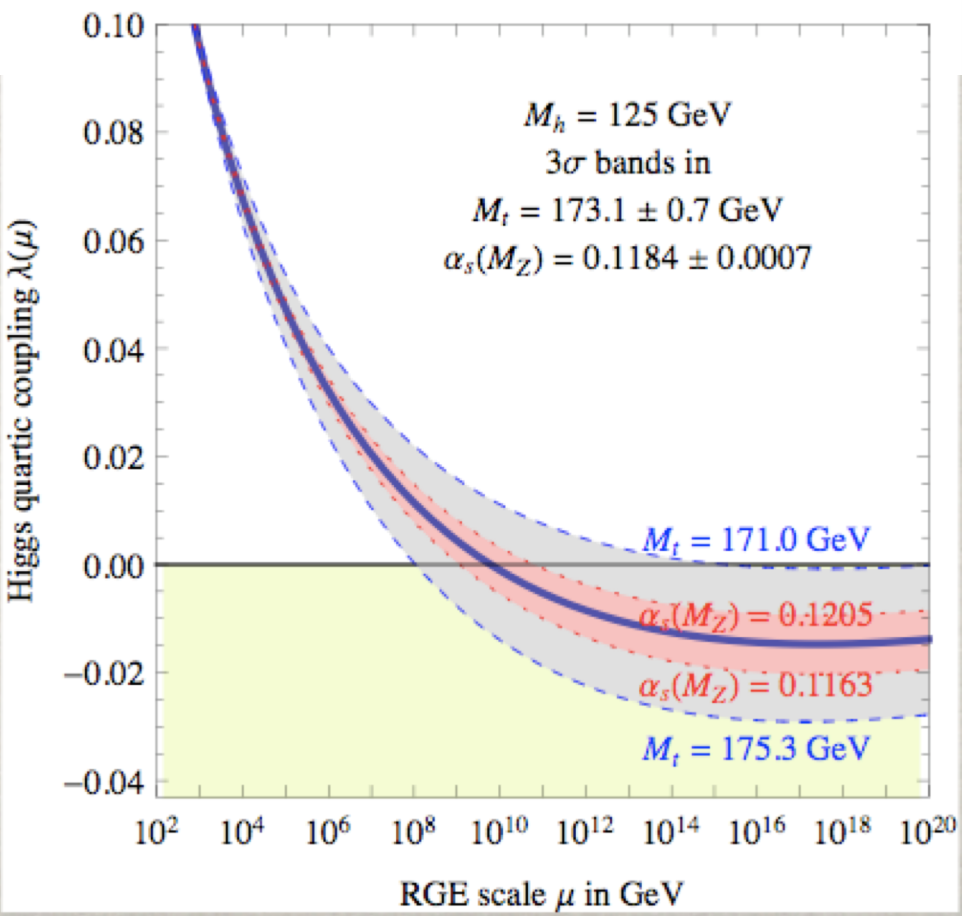




Combining threshold scan and top-reconstruction:

$\Delta m_t(\overline{MS}) < 50$ MeV, $\Delta\boldsymbol{\alpha}_s < 1\%$

→ Sufficient to decide on the SM vacuum stability!



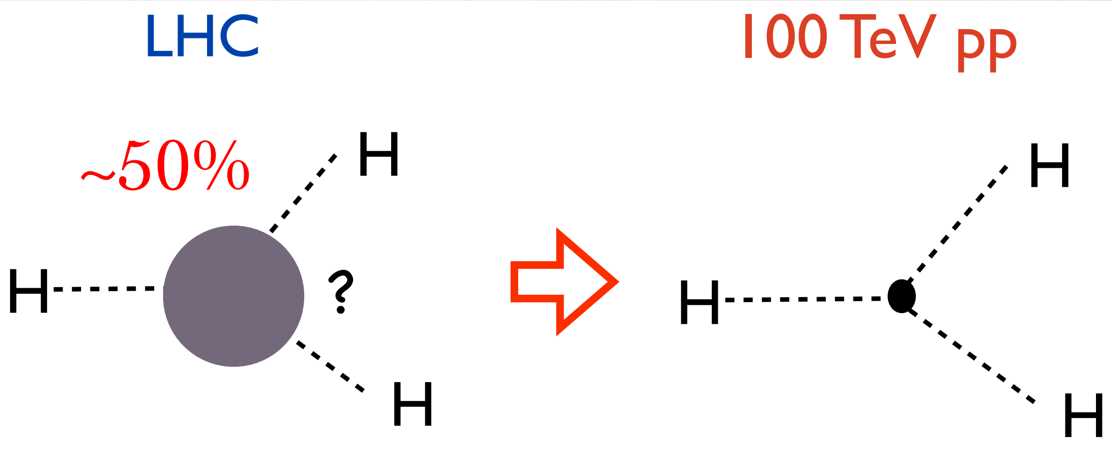
• Toward Energy Frontier

ILC: 0.5 – 1 TeV, CLIC: 1.4 – 3 TeV

a. Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2}m_H^2 H^2 - \frac{g_{HHH}}{3!}H^3 - \frac{g_{HHHH}}{4!}H^4$$

$$g_{HHH} = 6\ \ v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6\ \ = \frac{3m_H^2}{v^2}.$$



Triple coupling sensitivity:

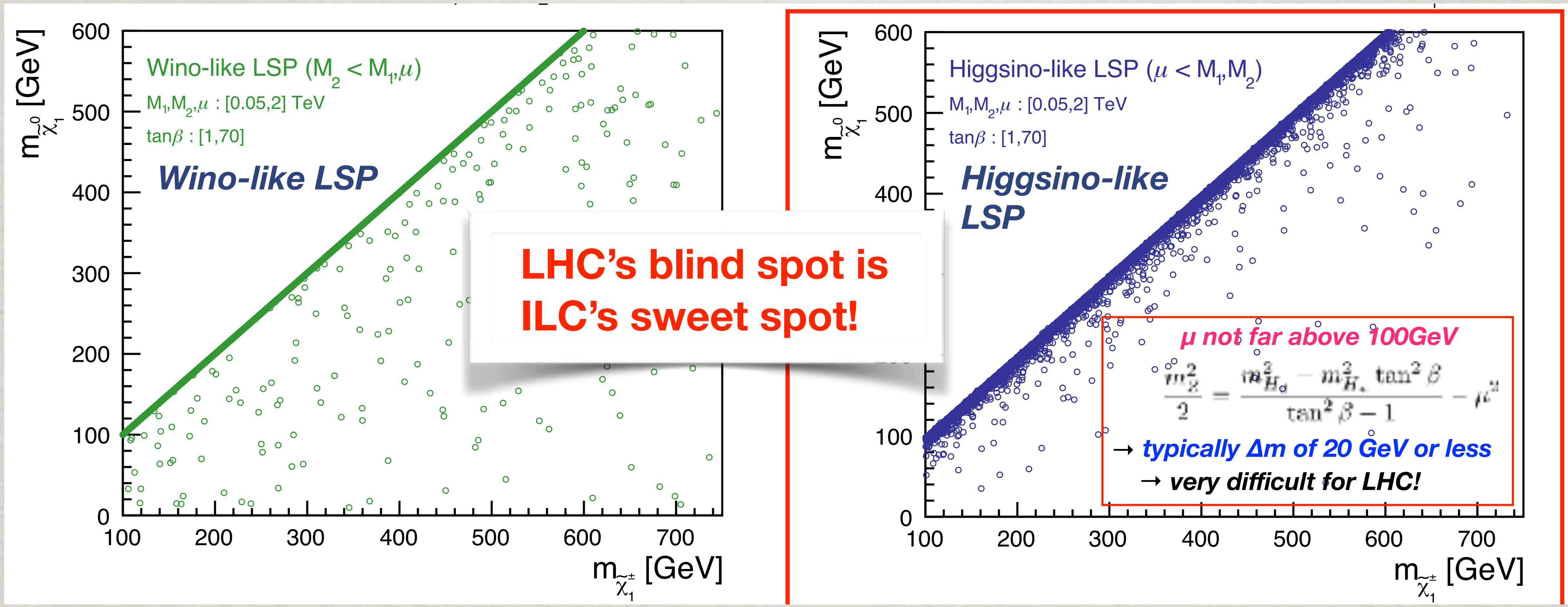
ILC arXiv:1506.07870 CLIC Report: 1307.5288v3

	0.5 TeV	1 TeV(2 ab^{-1})	1.4 TeV	3 TeV
λ_{hhh}	26%	10%	21%	10%

Test the shape of the Higgs potential better than O(1) deviations, conclusive on the fate of EW-phase transition!

b. New particle discovery: e.g. electroweakinos

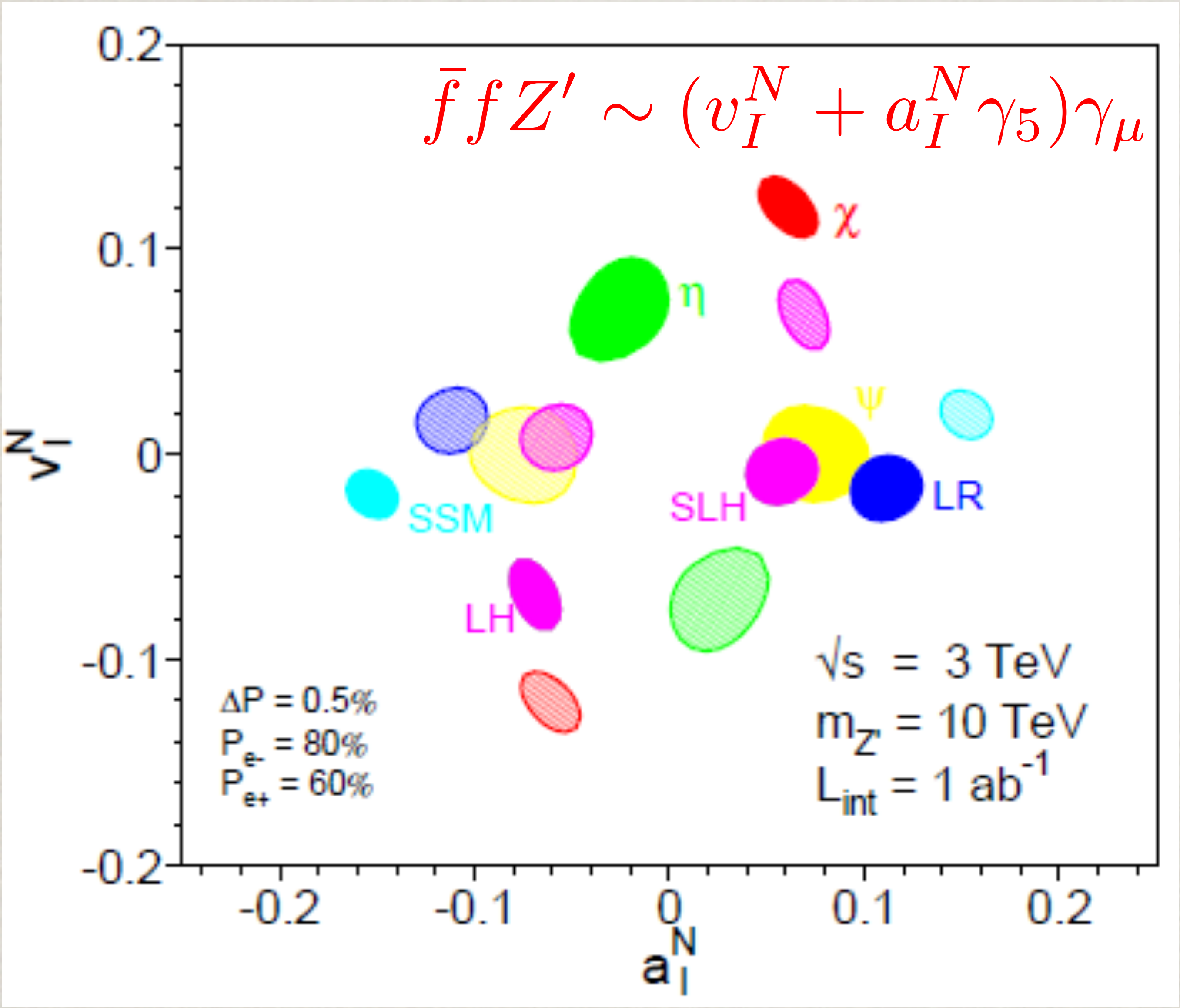
Keisuke Fujii



Discovery of an X: $M_x < E_{cm}/2$

Sensitive to $M_x^* >> E_{cm}$!

c. (virtual) Z' resolution: beam polarizations



EPJ-C:
arXiv:1504.01726

For a more dedicated polarization study, see: arXiv:hep-ph/0507011

Fig. 121 Top: Resolving power (95% CL) for $M_{Z'} = 1, 1.5$, and 2 TeV and $\sqrt{s} = 500$ GeV, $\mathscr{L}_{\rm int} = 1{\rm ab}^{-1}$, $|P_{e^-}|$ =80%, $|P_{e^+}|$ =60%, for leptonic couplings based on the leptonic observables σ, $A_{\rm LR}$, $A_{\rm FB}$. The couplings correspond to the E_6 χ, LR, LH, and KK models. From Ref. [905]. Bottom: Expected resolution at CLIC with $\sqrt{s} = 3$ TeV and $\mathscr{L} = 1$ ab^{-1} on the "normalised" leptonic couplings of a 10 TeV Z' in various models, assuming lepton universality. The mass of the Z' is assumed to be unknown. The couplings correspond to the E_6 χ, η, and ψ, the SSM, LR, LH and SLH models. The couplings can only

Beam polarizations help for chirally coupled particles:

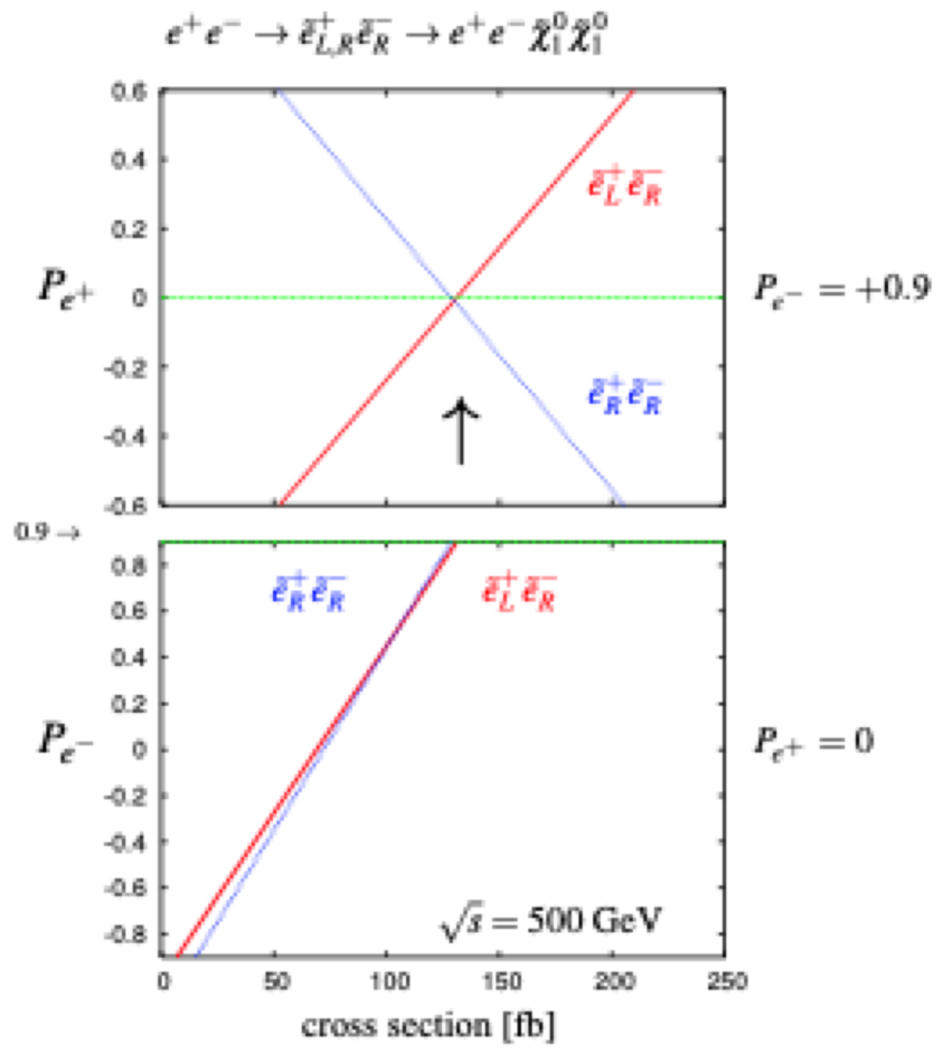


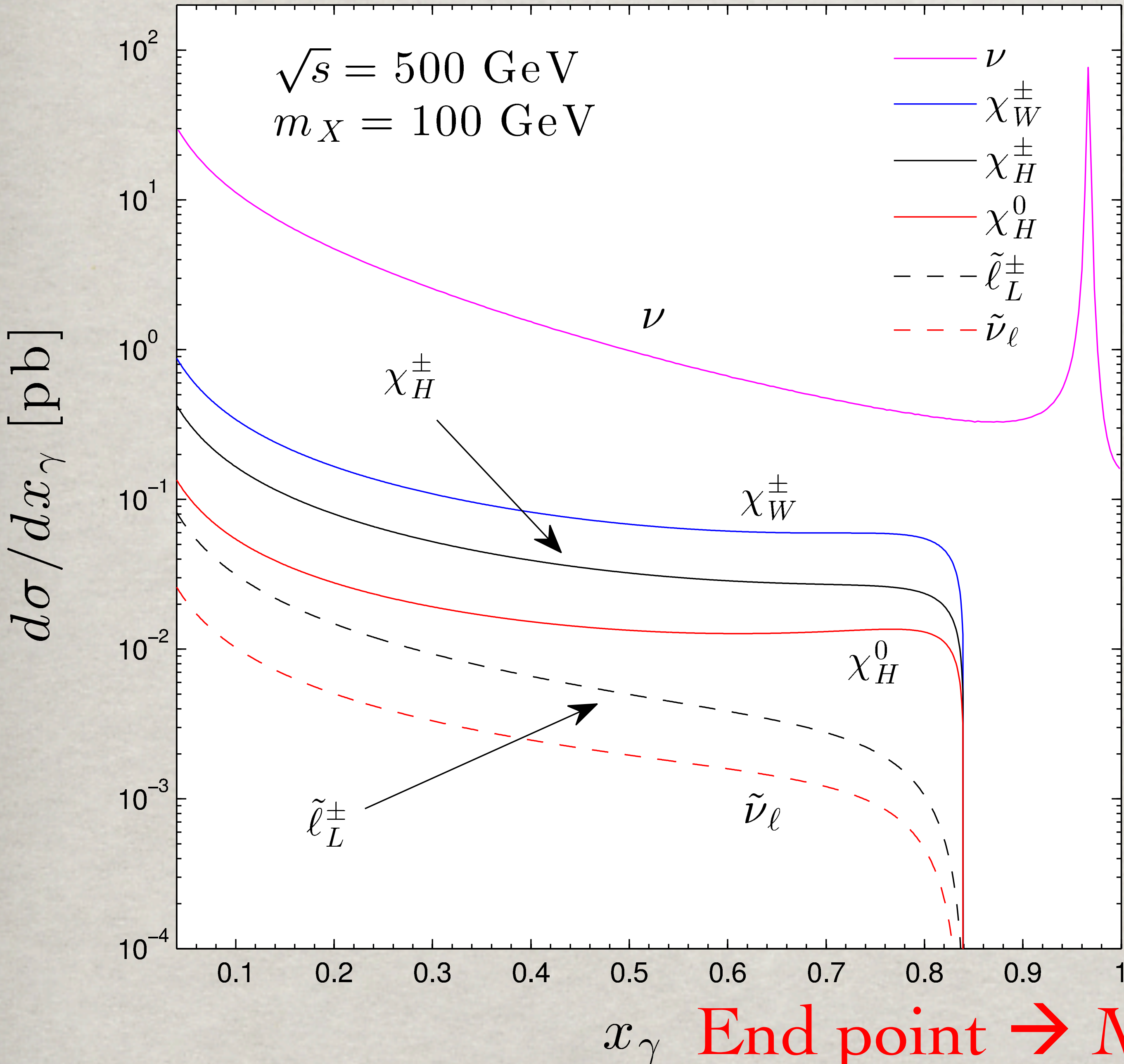
Fig. 5 Polarized cross sections versus P_{e^-} (bottom panel) and P_{e^+} (top panel) for $e^+e^- \to \tilde{e}\tilde{e}$-production with direct decays in $\tilde{\chi}^0_1 e$ in a scenario where the non-coloured spectrum is similar to a SPS1a-modified scenario but with $m_{\tilde{e}_L} = 200$ GeV, $m_{\tilde{e}_R} = 195$ GeV. The associated chiral quantum numbers of the scalar SUSY partners $\tilde{e}_{L,R}$ can be tested via polarized $e^\pm$-beams.

EPJ-C:
arXiv:1504.01726

d. DM searches & mass determination:

$e^+e^- \rightarrow X\,X\,\gamma$

$E_\gamma = (s - M^2_{xx})/2\sqrt{s}$



End point → M_X

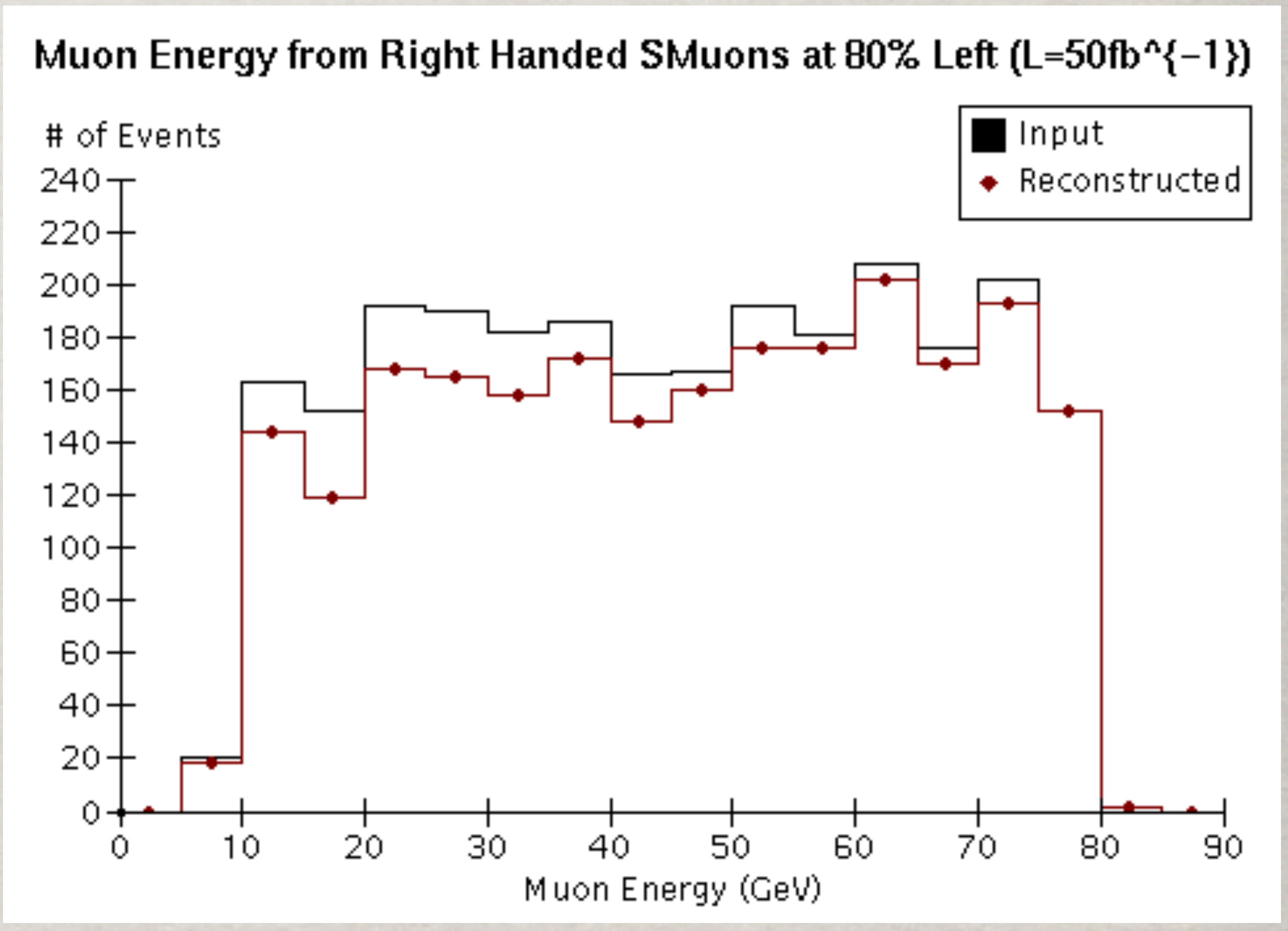
TH et al. arXiv:1503.08538

$e^+e^- \rightarrow \tilde{\mu}^+_R\,\tilde{\mu}^-_R$

with two – body decays : $\tilde{\mu}^+_R \rightarrow \mu^+\tilde{\chi}0$

$$E^0_\mu = \frac{M^2_{\tilde{\mu}R} - m^2_\chi}{2M_{\tilde{\mu}R}}$$

$$(1-\beta)\gamma E^0_\mu \leq E^{lab}_\mu \leq (1+\beta)\gamma E^0_\mu$$



End points → 2 Masses

hep-ex/0106056

$\sqrt{s}$/GeV:	92,160	240	350	500	1000	3000	threshold scans required
Higgs							
m_H	–	x	x	x	x	x	x
Γ_{tot}	–	–	x	x			
$g_{c,b}$	–	x	x	x		x	
g_{ttH}	–	–	–	x	x		
g_{HHH}	–	–	–	x	x	x	
$m_{H,A}^{SUSY}$	–	–	–	x	x	x	x
Top							
m_t^{th}	–	–	x				x
m_t^{cont}	–	–	–	x	(x)	(x)	
A_{FB}^t	–	–	x	x			
$g_{Z,\gamma}$	–	–	–	x			
g_{FCNC}	–	–	–	x	x	(?)	
Electroweak Precision Observables							
$\sin^2\theta_{\mathrm{eff}}$(Z-pole)	x					(x)	
m_W^{th}	x						x
m_W^{cont}		x	x	x	(x)	(x)	
Γ_Z	x						x
A_{LR}	x						
A_{FB}	x						
SUSY							
indirect search	x	x	x				
direct search	–	–	x	x	x	x	x
light higgsinos	–	–	x	x			x
parameter determination	–	–	x	x	x		x
quantum numbers	–	–	x	x	x		x
extrapolations	–	–	–	x	x	x	x
ν mixing							
θ_{23}^2	–	–	x	x			
Dark Matter							
effective-field-theory	–	–	–	x	x	x	
non-relativistic	–	–	x	x	x	x	
Extra gauge bosons							
indirect search $m_{Z'}$	x	–	–	x	x	x	
v'_f, a'_f	–	–	–	x	x	(x)	
$m_{W'}$	x	–	–	x	x	x	
direct search	–	–	–	–	–	x	x

Table 1 Physics topics where the e^+e^--Linear Collider provides substantial results at the different energy stages that are complementary to the LHC. The examples are described in the following chapters as well as in [7–9, 11–13, 23, 24, 26, 27, 48, 49].